Avalanche dynamics in a three-dimensional pile of rice

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In this thesis, I have studied the avalanche dynamics and surface properties of a three-dimensional experimental pile of long-grain rice. I chose this system to test the predictions of SOC, most of which are not easily accessible in natural systems, such as earthquakes, snow avalanches, forest fires, and biological evolution. The motivation for this work is given in Chapter 1.

In Chapter 2, I present the concept of SOC with its two hallmarks, power-laws and fractals. Then I describe the archetype of SOC, the BTW sand pile model, the rice pile models, and the Bak-Sneppen evolution model. In addition, I give a short review of a few natural systems, which are thought to exhibit SOC behavior. In Chapter 3, I describe our experimental system, the three-dimensional pile of long-grain rice. The setup is described in detail. I use the method of monocular stereoscopy which consists of projecting a pattern, in our case a set of colored lines, on the surface of the pile and taking an image with a charge-coupled-device (CCD) camera at a non-zero angle with respect to the projection direction. In the last section of this Chapter, I show, step-by-step, how these two-dimensional images of the surface of the rice pile are transformed into three-dimensional height maps.

In Chapter 4, I show that the three-dimensional pile of long-grain rice exhibits self-organized criticality. The response of the system to slow external driving are avalanches of all sizes, which are identified directly from the height differences between consecutive reconstructed surfaces. I find that the size distribution of these avalanches is a power-law over more than three orders of magnitude, with an exponent of $\tau = 1.11(2)$. I also determine the fractal dimensions of the avalanches using the box counting method and find a surface fractal dimension of $d_b = 1.80(2)$ and a volume fractal dimension of $D = 2.42(4)$. In addition, more stringent criteria of SOC are also fulfilled in our system. These are the finite size scaling of the avalanches and an intimate connection between the avalanche exponents (τ, D, and d_b) and the exponents that describe the rough surface left behind by these avalanches: the roughness exponent α and the growth exponent β. From the roughness analysis, I find $\alpha = 0.61(2)$ and $\beta = 0.33(2)$, which is in good agreement with the values obtained using the scaling relations $\alpha = D - d_b = 0.62(4)$ and $\beta = \frac{1-d_b/d}{2-\tau} = 0.29(3)$. These results show that our experimental rice pile exhibits SOC dynamics and can be used to gain further insight into the behavior of these systems. For a thorough understanding, however, it is important to understand how the system approaches the critical state. In Chapter 5, I find that the envelope of the maximum slope of the three-dimensional rice pile approaches its critical value as a power-law with an exponent $\delta = 0.78(4)$. Assuming a theoretical relation, based on extremal dynamics, δ can also be obtained from the avalanche exponents in the critical state: $\delta = 1 - \frac{1-d_b/D}{2-\tau} = 0.71(3)$, which is in good agreement with the experimentally obtained value. In conclusion we can say, that the way our

SOC system approaches its critical state is dictated by the critical state itself. In Chapter 6, I present the scaling properties of the surface of the three-dimensional pile of rice. I study the different moments of the height-height correlation function and find temporal multi-scaling in the critical state, while the transient state is characterized by generic scaling. This multi-scaling suggests again that the rice pile reaches its critical state through a process of self-organization and not through Langevin dynamics. According to the predictions of SOC, next to the usual dynamic correlation length there is an additional transient correlation length present in the critical state leading to the observed multi-scaling. In addition, I observe generic scaling in space, showing that there is only the usual correlation length observed in space for the critical state.

In Chapter 7, I find that by only changing the boundary condition of the three-dimensional pile of rice, the distribution of avalanche sizes changes. If the foot of the pile rests on a flat surface, the distribution of the avalanche sizes is a power-law. However, if the foot of the pile coincides with the edge of the box (a boundary condition similar to that in the sand pile experiments) quasi-periodic large avalanches are observed, while the distribution of small and medium size avalanches remains a power-law. The system spanning avalanches are promoted by the sideways propagation of the avalanche along the foot of the pile. Hence, I conjecture that the quasi-periodic avalanches observed in some sand pile experiments are also due to the boundary condition.

In Chapter 8, I study the local and global waiting time distribution in the experimental rice pile and in a simulated pile based on the two-dimensional Oslo model. The distribution of local waiting times gives the probability of a second avalanche returning to the same region in the pile, while the global waiting time is the time elapsed between two consecutive avalanches independent of their place of occurrence in the pile. I find that both the global and the local waiting times have an exponential distribution for the experimental and the simulated pile. This shows that both in experiment and simulations the avalanches are not correlated in time, which means that they are not predictable.

In Chapter 9, I present the effects of fast driving on the distribution of avalanche sizes in a simulated pile of rice. The simulations are performed on the Oslo rice pile model generalized to two dimensions. The driving of the pile is such that particles are added also during the evolution of the avalanches. I determine the exponent of the distribution for each driving rate from a finite size scaling analysis. I find that as the driving rate increases, a hump appears in the large avalanche regime, while the distribution of small avalanche sizes remains a power-law independent of the driving rate. The apparent value of the exponent of this distribution is influenced by the presence of the hump. I have investigated this question only numerically as the feeding mechanism of the experimental pile does not allow for driving rates high enough for our purposes.

In Chapter 10, I study a different system which was shown to exhibit SOC behavior. Here I study the flux penetration in superconducting thin films, although not from the point of view of SOC. The samples investigated have a multiply connected geometry: a square with a rectangular hole and a square with a square hole rotated by 45 degrees. The results of the magneto-optical experiments and our numerical simulations are in good agreement. However, neither of them shows the unexpected field distribution after full flux penetration is reached, with discontinuity lines perpendicular to the edges of the samples, observed previously by Chandran [Physica C 289 (1997) 22] in his simulations on Josephson Junction Arrays.